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Magnetic Materials for Power Applications

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The Final Proceedings for ADVANCED MAGNETIC MATERIALS FOR MORE-ELECTRIC MILITARY VEHICLES AND ELECTRIC PULSE POWER SYSTEMS(AVT-060), 26 June 2000 - 29 June 2000. Topics include: More Electric Airplane, Thermal Management, Rare Earth Magnets, Soft Magnetic Materials, Electric Weapons, Electrodeposition Technique, All Electric Vehicle, Magnetic Domains, Magnetic Nanoparticles, and Application of Novel Magnetic Materials. This was a NATO East-West Partnership for Peace Conference held in Marathon, Greece on 25-30 June, 2000.

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MAGNETIC MATERIALS FOR POWER APPLICATIONS

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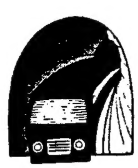


CONTENTS

MAGNETIC MATERIALS FOR POWER APPLICATIONS

		APPLICATIONS	FUNDAMENTAL & TECHNICAL MAG-NETISM	CHARACTERIZATION	MATERIALS	NOVEL PROCESSING TECHNIQUES
Time	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
8:30 - 9:00		"Opening Remarks" H. Weinstock (USA)				
9:00 - 10:00		"All Electric Vehicle" W. E. Brand (Germany)	"Introduction to Magnetism-Magnetic Interactions" H. Szymzhak (Poland)	"Magnetic Measurement Tech-niques" M. Mikhov (Bulgaria)	"Rare Earth Magnets" G. C. Hadjipanayis (USA)	"Gas Atomization Tech-niques and Sintering" G. Brecharya (Ukraine)
10:00-11:00		"Electric Weapons" F. Jamet (France)	"Magnetic Anisotropy" M. McHenry (USA)	"Novel Compaction Tech-niques" B. Chelluri (USA)	"It All Starts With Iron" A. S. Arrott (Canada)	"Magnetic Annealing" H. Chiriac (Romania)
11:00-11:30			COFFEE			
11:30-12:30		"Thermal Management in Power Systems" G. Khalil (USA)	"Rare Earth Intermetallic Compounds" A. S. Ermolenko (Russia)	"Microstructure and Mag-netic Domains" Josef Fidler (Austria)	"Nanocrystalline Soft Mag-nets" L. Varga (Hungary)	"Electrodeposition Techniques" M. L. Trudeau (Canada)
12:30-1:30		"More Electric Airplane" Alan Janiszewski (USA)	"Search for New Phases for Advanced Magnets" V. P. Menushenkov (Russia)	"Magnetic Domains" Y. G. Pastushenkov (Russia)	"Magnetic Nanoparticles" S. Majetich (USA)	"Future Trends and Directions" Round Table Discussion
1:30 - 5:00			SIESTA			Closing Remarks
5:00 - 6:00	REGISTRA-TION	"Applications of Perma-nent Magnets to Electric Machinery" H. Leupold (USA)	"Magnetic Hysteresis" H. Kronmuller (Germany)	EXCURSION	"Composites/Nanocompos-ites" K. Unruh (USA)	
6:00 - 7:00	REGISTRA-TION	"Applications of Novel Magnets" "D. Howe (UK)	"Magnetic Hysteresis" H. Kronmuller (Germany)	EXCURSION	"Exchange Coupled Nanocomposite Magnets" T. Chui (USA)	
7:00 - 7:30	RECEPTION	Discussion	Discussion	EXCURSION	Discussion/Comments	

Speaker: BDir W. Brand
BWB KG I 6, Koblenz, Germany

Marathon, 26th June 2000

NATO Workshop
on Advanced Magnetic Materials
for All-Electric Military Vehicles and Electric Pulse Power Systems
in Marathon, Greece from 25 to 30 June 2000

"All Electric Vehicle"

Abstract:

Benefits of electrical energy and progress in electrical technologies

The main characteristic of the „All Electric Vehicle“ (AEV) is the overall use of electric energy for all functions of the vehicle. If there are combat missions involved like survivability and lethality, we talk about an „All Electric Combat Vehicle“ (AECV). Hereafter, the abbreviation AEV for both applications will be used.

The AEV systems may have the following configurations:

- Pure electric: only electric supply components are used (e.g. battery or fuel cell).
- Diesel or turbo electric: the prime mover is a diesel engine or gas turbine
- Hybrid electric: a vehicle with the capability to run either by generated or stored electrical energy

In principle those AEV features and performances are to be addressed:

- electric drive of the vehicle,
- supply of command, control, communication and information systems,
- electric brake and regeneration of braking energy,
- electric supply of auxiliary subsystems like fan drives and actuators,
- electric supply of additional electric consumers within the vehicle,
- electric power supply of external consumers,
- electric power supply for electric weapons like electric guns or directed energy like Laser, High Power Microwave and electric armor.

Why are great efforts made to investigatethe field of AEV?

The reason is the growing importance of electrical systems based on the physical characteristics of electric energy allowing

- elementary electrical conversion, distribution, control,
- simple and effective interaction with chemical processes (e.g., ignition of internal combustion engines or ammunition),
- simple transformation (e.g. into force, heat, light).

Thus, many benefits arise, e.g., for components like

- power distribution and power summation at will (allowing free arrangement of components),
- modular subsystems (redundancy and better utilization of space),
- lack of hydraulics (no hazardous liquids, clean compartment)

and for systems like

- homogeneous power systems,
- energy management including peak–power,
- manifold growth potential,
- automation, remote control, robotics,
- high reliability, internal diagnostics,
- beneficial life-cycle costs (maintenance free, low wear, high efficiency),
- less training,
- auxiliary power supply.

These benefits have been well known for more than 100 years many applications and technical solutions have been created since the beginning of the industrial age, but a real success and breakthrough could not be achieved for a long time.

Thanks to the progress made in the fields of electronic controllers, computers, permanent magnets and power electronics during the last thirty years, new electrical technologies now allow electrical equipment with sufficient power and energy density for use in vehicles. In addition, electrical storage components also have improved tremendously. New electro-chemical storage media such as improved batteries, as well as flywheel energy storage systems with electrical input and output provide an improved basis to supply electrical vehicle systems.

Following are some examples of this progress:

We all are aware of the tremendous worldwide use of electronic controllers, processors and computers. They are essential to take full advantage of the AEV. Concerning magnetic materials the maximum energy density (given by the BH product) has improved by a factor of 40 in comparison to steel. Nearly within the same time frame, power electronics also have improved by a similar amount. A further big step in performance will be expected utilizing the emerging SiC technology.

Components / Concepts for AEV

Electrical machines based on permanent magnet (PM) material for excitation have been in use for quite some time. But their insufficient energy density did not allow for beneficial vehicle integration. This also applied to power electronics. Improved technologies now permit the realization of high-power and high-energy drive components such as electric generators, motors, power converters, controllers and power management units.

The DC power link plays a very important role in the electric architecture of the AEV. Here, the electric energy is available to its largest extent. First, there must be energy storage to start the prime mover. Once the engine is running, the full power of the generator can be used for driving. A multi-engine concept also is feasible. The processor control unit governs the operation and additionally provides power management for the AEV.

This describes the common AEV system. But regenerative braking and the high-energy / high- power storage system, either a flywheel or a battery, provides additional power. Only an electrical system allows the easy combination of these power sources, creating new AEV

features and performances which are not feasible with conventional vehicle systems. additional subsystems for AC and DC power units, such as those needed for weapons – naturally being very important for the mission - only participate as consumers.

The essential components for mobile systems using new magnetic materials and several AEV concepts - wheeled or tracked - are discussed in terms of their benefits for weight, volume, efficiency, and technical and military performance.

Finally, examples of actual electric vehicles are presented.

Conclusion

The AEV system utilizes a single form of energy and provides one basic technology in a homogeneous design for power generation and regeneration, and for the power supply of all subsystems. The drive and mission components, even the control elements and sensors, form a homogeneous system structure assuring direct interaction with power management and mission-control devices. In addition, new high-power energy storage systems allow for new features such as peak-power management for highly-improved dynamic mobility, survivability and silent watch.

Several commercial vehicles and military prototypes are already on the road being tested in order to evaluate and improve electric-drive technologies. New magnetic materials are an essential key element for those AEV systems. But additional effort is still necessary to improve the design and performance of Permanent Magnet Machines. Therefore, the following areas for further work are addressed:

Requirements	Consequences
• high remanence B_r [T]	high torque M [Nm]
• high intrinsic coercive force H_{CJ} [kA/m]	high stability against demagnetizing fields
• high specific energy product $(B\cdot H)$ [kJ/m^3]	high power capability or low construction volume
• high thermal resistance	demagnetization only at high temperatures
• high electrical resistivity	low losses by eddy currents
• high resistance against humidity and reagents	long life and corrosion resistance
• low dependence on temperature of: - remanence B_r - intrinsic coercive Force H_{CJ}	decrease of temperatures causes lower: - reversible reduction of the B-field - irreversible damages of magnets at higher temperatures
• beneficial mechanical features (e.g., sturdiness, flexural strength,...)	long life, simple mechanic construction

It is hoped that this workshop will give beneficial inputs to accelerate adequate Permanent Magnet Material development programs.

ELECTRIC WEAPONS

Dr. F. Jamet and Dr. P. Lehmann
French-German Research Institute of Saint-Louis

presented at the NATO East-West Workshop, Marathon, Greece
June 26-30, 2000

Summary

The presentation will be devoted to three types of weapons:

- High Power Microwaves (HPM),
- ElectroMagnetic Railguns (EM),
- ElectroThermalChemical (ETC) guns.

The characteristics of the weapons, in the frame of conventional military applications will be examined in order to determine the specifications for the electric pulsed power supplies: energy, power, voltages, current intensities, pulse duration/rise/decay time, etc.

For HPM weapons, 1 µs to 10 µs current pulses of more than 10 kA and voltage levels of 100 kV to 1 MV are necessary. For EM railguns the electrical energy necessary for one shot ranges between 1 MJ and 50 MJ, depending on the military application, and the current reaches several MA.

Examples of energy/power storage architectures and pulse forming networks based on the use of capacitor banks and superconducting coils will be analyzed.

The needed characteristics of the components such as high discharge capacitors, switching systems or connecting parts will be described and the expected technology improvements allowing to lower the masses and volumes will be examined.

Finally, we shall describe in details the 10 MJ ISL railgun facility in order to give an overview about the main issues of such weapons. The electrical sliding contact studies, the barrel technology as well as the used measurement techniques will be presented. We also shall show examples of numerical simulation of the EM behaviour of the rails-armature coupling.

THERMAL MANAGEMENT IN POWER SYSTEMS

Ghassan Khalil

Electric drives have been investigated through the 20th century for their potential advantages in vehicle propulsion. In every attempt Military and commercial vehicle developers always concluded that electric power is adequate but presents challenges that must be overcome prior to application. With the evolution of the technology several advances have been made which have placed electric and hybrid electric drives in the forefront of the candidates of future power and energy alternatives.

Two of the most important achievement-promoting advancements for electric drives are advanced magnetic materials with high energy product, thus high torque and power densities and power semiconductors. Devices with higher power density, higher efficiency, better thermal performance, improved reliability and lifetime, and better control characteristics have recently been developed. However, the silicon-based power devices have a limited operating temperature range (less forgiving than the magnetic materials) and require a relatively low temperature coolant. This adds a cooling burden to the powertrain and presents a great challenge to the vehicle integrators.

This paper discusses the military vehicle requirements, the application of advanced magnetic materials and their impact on the cooling system. It also covers the promising approaches to overcoming the cooling issues.

MORE ELECTRIC AIRCRAFT
(Abstract)

To be presented at the East-West NATO Workshop on "Magnetic Materials for Power Applications" on 26 June, in Marathon, Greece.

Dr. A. M. Janiszewski, USAF
Propulsion Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433-7251

A national initiative is underway to develop and test more electric aircraft (MEA) technologies and is being led by the U.S. Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio. The MEA concept is based on utilizing electric power to drive aircraft subsystems which are currently driven by a combination of hydraulic, pneumatic, electric and mechanical power transfer systems. A major objective of this effort is to increase military aircraft reliability, maintainability and supportability and to drastically reduce the need for ground support equipment. Conventional aircraft secondary power systems, addressing the auxiliary, starting, and emergency power requirements are comprised of complex, high maintenance, hybrid subsystems. Mechanical, electrical, hydraulic, and pneumatic power systems are used to transfer power from the point of generation to the final utilization. The combined logistics to support these subsystems is substantial. Based on rapidly evolving power electronics, fault tolerant electrical power distribution systems, and electric driven flight control actuator systems, increasing the use of electric power is seen as the direction of technological opportunity. Predicted aircraft improvements, including a reduction in required logistics support and an overall increase in available electrical power, will be presented. These improvements will be realized with the further advancement of key MEA technologies, including magnetic bearings, aircraft integrated power units (IPU), and starter/generators (IS/G) internal to an aircraft main propulsion engine. These advanced developments, as well as ground and space power applications, will be discussed, as they are the driving force for the new emphasis on high temperature and high strength magnetic materials for power applications.

NOVEL APPLICATIONS OF PERMANENT MAGNETS TO ELECTRICAL MACHINERY

Herbert A. Leupold

Advances in permanent magnet materials and design technology have made possible electrical generators and motors that are much more compact, have much less stray field and produce more energy per structural mass than do conventional ones. The simplest of these are essentially rotating Halbach structures (or magic cylinders) with electric coils in their interior cavities. Slightly more complex are counter-rotating, nested Halbach structures which feature less eddy current loss than the simpler configurations of the same mass and output.

Approximations to Halbach structures known as magic mangles afford considerable reduction in the movements of inertia of the rotating parts thereby resulting in greater rotational responsiveness. Also brittle magnet materials are subject to much less stress in mangles than in equivalent cylinders thus affording much higher rotational frequencies. Magic mangles are much easier to manufacture than the equivalent magic rings though at the expense of small losses of magnetic field. Comparisons made with more conventional structures favor the magic mangles. In one case a magic mangle generator produces seventy five percent more voltage with only one fourth the structural mass of a comparable conventional configuration. Similar advantages exist for other cylindrical and mangle type embodiments indicating potential advantageous applications in missiles, spacecraft, airborne vehicles, and portable surface devices.

Also discussed in this presentation is a variety of other promising electro-mechanical devices and components such as field-gradient activators, permanent magnet rotors with gradual azimuthal periodicity in orientation, and novel magnetic bearings.

Novel Applications of Magnets

Professor David Howe
Department of Electronic and Electrical Engineering
University of Sheffield

Abstract

As a consequence of recent advances in permanent magnet materials, as well as developments in power electronics and digital control technology, many new and novel designs of machine/actuator are emerging for applications in different market sectors. The presentation will focus on research which is being undertaken at the University of Sheffield on some specific permanent magnet machine/actuator systems.

- **Modular, fault tolerant, permanent magnet brushless motors:** The phase windings are magnetically, electrically and physically isolated, and can be designed to limit the short-circuit current to the rated full-load current of the machine, which is conducive to fault tolerance. Further, since only alternate stator teeth carry coils, such motors are conducive to low cost modular construction. Thus, they are appropriate for both safety critical and cost-sensitive applications, such as aircraft flight control surface actuation, integrated start-alternator and traction drives, and marine propulsion. However, precautions have to be taken to minimise rotor induced eddy currents.
- **Multi-degree-of-freedom-spherical actuators:** Controlled motion of a spherical permanent magnet rotor with multi-degrees-of-freedom is achieved by employing a diametrically magnetised rotor and three orthogonal pairs of stator coils – to facilitate 'pan and tilt' excursions of ±45°, or a 4-pole parallel magnetised rotor and four sets of non-orthogonal coils – to additionally facilitate continuous rotation. By eliminating the need for a separate motor/actuator for each axis, as is generally required for multi-degree-of-freedom actuation systems, the dynamic performance is improved, whilst the system is both lighter and more efficient. Potential applications include robotics, flexible manufacturing, active vision systems and force-feedback joysticks.
- **Halbach magnetised permanent magnet brushless motors:** The combination of a multipole Halbach magnetised rotor and a stator with a non-overlapping (concentrated) winding offers several potential advantages, such as an inherently sinusoidal airgap field distribution and emf waveform, and a very low cogging torque. Thus, likely applications include servo motors, for which a potentially low cost manufacturing route is the injection moulding of Halbach orientated anisotropic bonded NdFeB ring magnets from HDDR-derived moulding compound.
- **Tubular, linear brushless motors:** Tubular motors comprise a multi-pole permanent magnet thrust rod and a moving coil thrust block. By employing a two-phase iron-cored thrust block, both a high thrust force capability and a high closed-loop position bandwidth can be achieved, enabling direct-drive linear motors to complete with more traditional methods for generating controlled linear motion, in applications such as high-speed packaging/manufacturing. Tubular motors impose negligible net radial force on the bearing system and have no end-windings, which is conducive to low copper loss. However, design optimisation is required to minimise the cogging force which results from slotting (slot-pitch equals pole-pitch) and the finite length of the laminated iron cores of the thrust block, whilst consideration should be given to the level of the eddy current loss which is induced in the thrust rod during high speed operation.
- **Flywheel peak-power buffer for electric/hybrid vehicles:** The incorporation of a peak-power buffer in the power-train of electric/hybrid vehicles could significantly enhance their performance and improve consumer acceptance, by making acceleration/regenerative braking largely independent of the state-of-charge of the batteries, extending the cycle-life of the batteries and increasing the vehicle range – by enhancing power-train efficiency. One potential technology is a high-speed flywheel, based around a cylindrical fibre composite rim, with an integral brushless motor/generator for converting kinetic energy to electrical energy, and vice-versa, and which is supported on active/passive magnetic bearings. However, particular consideration must be given to minimising power losses so as to obtain a high 'round-trip' efficiency and to limit the temperature rise of the rim, which rotates in a high vacuum so as to minimise the aerodynamic loss.
- **Reciprocating moving-magnet actuators for resonant electro-mechanical systems:** 'By matching the system compliance to the total moving mass, and thereby making the mechanical resonant frequency coincident with the electrical excitation frequency maximum displacement of the moving-magnet armature and the coupled load and maximum system efficiency are achieved. The high energy product to mass ratio of rare-earth magnet materials can be exploited to advantage in such actuators. Potential applications include air-compressors, fuel pumps, artificial heart devices, etc.

INTRODUCTION TO MAGNETISM-MAGNETIC INTERACTIONS

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Some basic interactions governing the properties of magnetic materials at the atomic scale are discussed on an introductory level. The essential interactions determining the magnetic moments, the temperature of magnetic ordering and the type of magnetic order are the exchange interactions, spin- orbit coupling and the crystal field acting on magnetic electrons. The relative importance of each interaction term may strongly differ from one system to another due to different behavior of magnetic electrons. It will be shown that all magnetic interactions can somehow depend on the lattice distortions and therefore contribute to the magnetoelastic energy (and consequently - to the magnetostriction). The two non-local effects related to the demagnetizing fields and to the magnetostrictive self-energy are shown to have strong effect on the magnetic domain structure and on extrinsic properties of magnetic materials.

East-West NATO Workshop Partners for Peace: MAGNETIC MATERIALS FOR POWER APPLICATIONS

Magnetic Anisotropy

M. McHenry (USA)

Abstract

The physical basis for magnetic anisotropy, in terms of shape, magnetocrystalline, and stress (magnetostrictive) anisotropies will be introduced with emphasis on the quantum mechanical origin of magnetic anisotropies. The Landau theory of magnetic phase transformations will be introduced. Within the language of the Landau theory energy density, terms describing magnetocrystalline and magnetoelastic anisotropies will be illustrated. Each of these will be developed with an example of a current magnetic material which is important to power applications (or actuation). The temperature dependence of magnetic anisotropy will be developed within this framework. A local Landau theory will be described and used to illustrate important magnetic nanocomposites (soft/soft, hard/hard and hard/soft). These illustrations will include HITPERM soft magnets, 2:17 and 3:29 phase hard magnets, and spring exchange magnets. Surface and interfacial anisotropies will be discussed using nanocomposite ideas.

Rare Earth Intermetallic Compounds

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The studies of the physical properties of rare earth intermetallics began in 1950-th years, and the interest to this subject does not weaken up to now. The intermetallics between rare earth and 3d transition metals occured to be especially interesting and attractive. The permanent magnets and the magnetostriction materials with outstanding properties were developed on their base. These properties are realizing due to the confluence of two kinds of ions with 3d and 4f unfilled electron shells into one 3d-4f intermetallic. Namely this kind of rare earth compounds is a main subject of consideration in the present lecture.

The following topics will be touched:

1. The peculiarities of magnetic properties of 3d-4f metals.
2. The main types of the binary 3d-4f intermetallics.
3. Two-sublattice magnetic structures of 3d-4f intermetallics.
4. Exchange interactions and regularities of spontaneous magnetic moment formation.
5. The magnetocrystalline anisotropy and the magnetostriction.
6. The orientational magnetic phase transitions.
7. Alloyage influence on magnetic properties of 3d-4f intermetallics.

MICROSTRUCTURAL CHANGES AND COERCIVITY OF RARE-EARTH ALLOYS AND PERMANENT MAGNETS. THE SEARCH FOR NEW PHASES FOR ADVANCED MAGNETS

V.P. Menushenkov, A.S. Lileev, A.G. Savchenko
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The influence of the phases transformations in Sm-Co and Nd- Fe-B based alloys and sintered magnets during heat treatment on their histeresis properties are discussed. The main attention are focused on both the homogeneity regions of these phases and the intergranular regions. After an analysis of the crystal lattice parameters of the $SmCo_{5+-x}$ alloys and sintered magnets a hypotetic scheme of phases transformations and the boundary of homogeneity region are proposed. This scheme is compared and discussed with that previously obtained in other studies. The use of this scheme provides the better understanding of the structural mechanism of high coercivity obtained for the $SmCo_5$ based alloys enriched in Sm or Co. The evolution of the microstructure and coercive force during heat treatment are considered.

One of the unsolved question in the understanding of the properties of Nd-Fe-B sintered magnets is the role of heat treatment in the 450-600^{0}C range in developing of coercivity. Both the role of surface of the $Nd_2Fe_{14}B$ grains and the intergranular regions are analysed. Numerous investigations have been performed to study the phases composition and microstructure changes in the intergranular regions. The space lattice parameters of the $Nd_2Fe_{14}B$ phase vary unmonotonously with annealing temperature. After analysis of the hydrogen concentration in as-cast Nd-Fe-B alloy, sintered and heat treated magnets the effect of hydrogen in $Nd_2Fe_{14}B$ and intergranular Nd-rich phases is discussed. The study of model alloys of Fe-Nd system shown that their high coercivity is attributed to the metastable highly anisotropic A_1 phase forming during eutectic reaction. The structural changes in Nd and Nd-Fe alloys and the influence of A_1 phase in coercivity of Fe-Nd alloys and Fe-Nd-B magnets are considered.

The phases transformations in higher magnetic energy density Nd-Fe-B films with axial crystalline texture along the normal to the sputtering plane are discussed. The films were produced by ion-plasma sputtering of as-cast targets. The evolution of the microstructure and coercive force of the sputtering films during heat treatment are analysed.

In the search for new high performance hard magnetic materials it is desirable to look for Fe-Co based alloys with higher than 83 at.% transition metal concentrations. The magnetic properties of some rare earth (Yb) - Co-Fe-Mn alloys are compared and discussed.

Abstract for East-West NATO Workshop on "Magnetic Materials for Power Applications", Marathon, Greece, June 26 – 30, 2000

Magnetic Hysteresis

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Abstract
During the last few decades a large number of high-performance magnetic materials have been developed covering a wide range of permeabilities and coercivities. Permeabilities up to $\sim 10^6$ have been developed for nanocrystalline systems based on transition metals and coercivities up to 4 Tesla for sintered and nanocrystalline intermetallic compounds of rare earth metals. The basic properties of magnetic materials are their **intrinsic** material parameters as spontaneous polarization J_s, Curie temperature T_C, anisotropy constants K_i and magnetostriction λ_s. Usually, in general large values of J_s and T_C are required for all types of magnetic materials, whereas K_i and λ_s should be as small as possible for soft magnetic materials and rather large for hard magnetic materials. The extrinsic properties of the hysteresis loop as coercive field H_c, remanence J_r, initial susceptibility χ_0 and Rayleigh constant α_R depend sensitively on the microstructure of the material and in the case of small particles and thin platelets also on the size and shape. The characteristic properties of the hysteresis loop χ_0, H_c, α_R are the most exciting properties because their values may vary over 6 orders of magnitude which results from the relation between intrinsic properties and the microstructure.

In soft magnetic materials, crystalline or amorphous, the interaction between domain walls and the microstructure plays the dominant role for the hysteresis loop. For the case of dislocations it is shown that these govern the domain pattern as well as the magnetization processes.

In nanocrystalline magnetically soft materials as FINEMET, instead of domain wall displacements rotational processes dominate the magnetization process. Due to the random anisotropy effect in such systems a drastic decrease of the effective anisotropy constant takes place if the domain wall width exceeds the diameters of the grain size.

Whereas in crystalline soft magnetic materials the statistical theory of domain wall pinning give a quantitative interpretation of χ_0, H_c, α_R in the case of nanocrystalline materials the micromagnetic theory of the random anisotropy of statistically distributed easy directions allows a quantitative description of the properties of the hysteresis loop.

In hard magnetic materials as sintered and nanocrystalline magnets or individual single domain particles the hysteresis loops depend sensitively on the perfection of grains and the type of coupling between them. By means of computational micromagnetism on the basis of the Finite Element Technique the demagnetization of three characteristic nanostructures have been simulated: i) Magnetically decoupled

grains due to a paramagnetic intergranular phase. ii) Magnetically exchange coupled grains with grain boundaries of reduced material parameters. iii) Nanocrystalline composite systems where magnetically soft iron grains are magnetically hardened by exchange coupling with hard magnetic grains.

From these results detailed information for the tailoring of hysteresis loops by well defined microstructures has been obtained. It is shown that optimized magnetic materials require suitable intrinsic material parameters but also well-defined microstructures. By characteristic examples of modern magnetic materials the correlations between magnetization processes, magnetic structures and the microstructure are demonstrated.

MAGNETIC MEASUREMENT TECHNIQUES (CLASICAL METHODS)

M. Mikhov

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Mechanical forces on the magnetic moment, placed in a homogeneous or nonhomogeneous magnetic field, and magnetic field created in the space around the magnetic moment give the varieties of the direct methods for magnetic measurements. DC Faraday magnetometer (magnetic balance), Alternating Gradient Force Magnetometer and Torque Magnetometer are described as most popular techniques for magnetization and magnetic anisotropy studying, based on the force measurements. Vibrating Sample Magnetometer, SQUID Magnetometer, AC Susceptometer and Hysteresis Loop Tracer are given as examples of very commonly used methods, based on the flux measurements. The advantages and the limitations of the methods, such as sensitivities, accuracies, dynamical ranges, sample sizes, temperature and field ranges are noted. The influence of the demagnetizing field on the magnetization (*M* vs. *H*) curves is also briefly commented. The talk is not dealing with the different methods for interpretation of the experimentally obtained quantities.

Dynamic Magnetic Compaction (DMC) of Soft and Hard Magnet Powders

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Dynamic Magnetic Compaction (DMC) is an innovative net shape powder pressing technology that uses magnetic pulse forces to achieve full density in several material systems. Since the compaction duration is less than 1 millisecond, important dynamic effects occur in the powders which, when combined with the full density, yield properties for high performance. Additionally special microstructures and grain sizes of the starting powders can be preserved after DMC compaction. Different types of magnet powders are being compacted using this technology for DOD and Commercial applications. Amongst soft magnet powders these include resin coated soft iron powders for ignition core applications and nano iron-cobalt powders for high temperature DOD applications. In the hard magnet area, powders of SmCo (2:17) are being investigated for better mechanical and magnetic properties for high temperature DOD applications, bonded neo magnets for higher performance commercial applications and compaction of nano magnet powders such as Pr_{19} Co_{81} powders. In this presentation, an overview of the process, the properties of various compacted materials, technology features such as size, shape and dimensional tolerances that can be achieved in finished parts will be described.

Microstructure and Magnetic Domains

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The development of new hard and soft magnetic materials, the increasing information density in magnetic recording and the miniaturization in magnetic sensor technology lead to an increasing interest in the interaction between microstructure and magnetic domain structure. The shape and the detailed spatial arrangement of domains and domain boundaries determine the magnetic hysteresis or magnetization curve which describes the average magnetization of a magnetic material as function of the external field. The trend towards nanocrystalline magnetic materials and the improved availability of large scale computer power are the main reasons why micromagnetic modelling has been developing extremely rapidly in order to simulate the influence of the shape and the size of grains, of their magnetic intrinsic parameters and of precipitates on the formation of magnetic domains.

Micromagnetic modelling of the magnetization reversal process of magnetic nanoelements which are patterned structures at the submicron level show that the shape of elements become an important factor controlling the hysteresis. The worldwide interest in these elements is their potential for possible future application in high density magnetic data storage and microsensor applications. For use as patterned magnetic media each individual nanoelement would storage one bit. Thin films with exchange coupled nanocrystalline grains such as permalloy or cobalt will be used to fabricate the nanoelements. The physics of real magnetic materials and ultra small devices, such as patterned media, spin-valve devices and spin tunnel junctions, is complex, and the understanding of the magnetic switching behaviour is of great interest. Over recent years the investigation of nanostructured elements has become more advanced due to improvements in numerical micromagnetic methods on the theoretical side and high accuracy fabrication methods, such as electron beam lithography and focused ion beam techniques.

The search for novel soft and hard magnetic materials for high temperature advanced power applications and for magnets with highest energy density values is worldwide an active area of research. The nucleation and expansion of reversed magnetic domains and the pinning behaviour of the magnetic domain walls are the factors determining the coercive field or hysteresis of such materials.

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Magnetic domain structure and spin-reorientation process

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Abstract

Magnetic phase transitions, in general, are of considerable interest to the scientific community [1]. It is of great interest to study the phase transition occurring in the single crystals of intermetallic compounds since they offer other variety of magnetic for this type of study. From this point of view the tetragonal intermetallic compounds $Nd_2Fe_{14}B$, $R(Fe,Co)_{11}Ti$ (R=Tb, Dy) are of outstanding interest. By the change of magnetic constant they demonstrated all possible types of magnetic anisotropy (easy axis, easy cone, easy plane, easy axis + easy plane) and also the magnetic phase transition between them [2-4]. Therefore the intermetallic compounds $Nd_2Fe_{14}B$ and $R(Fe,Co)_{11}Ti$ are good model objects for study of the physical picture of magnetic phase transitions in tetragonal magnetics. On the other hand they are the main bases for the manufacturing of modern high-energy permanent magnets. In this sense the investigation of magnetic phase transition in tetragonal compounds is also very important for the best understanding of temperature dependence of demagnetisation processes in Nd-Fe-B and Sm-Fe-Ti permanent magnets.

The domain structure was investigated in the spin-reorientation region on the (100) and (001) planes and arbitrary oriented surfaces of $Nd_2Fe_{14}B$ and $R(Fe,Co)_{11}Ti$ single crystals with non-uniaxial magnetocrystalline anisotropy by means of the magnetooptical Kerr effect. The magnetic phase diagram of a tetragonal magnetic is calculated theoretically and the effect of domain structure on the nature of the phase transition is investigated. Domain-wall density calculations have been performed for the same domain wall orientations in tetragonal magnetics with all types of non-uniaxial magnetic anisotropy. On the basis of the observed domain configurations and domain-wall density calculations the possible models for the volume magnetization distribution and possibility of new domain wall types formation in tetragonal magnetics with "easy cone" and "easy plane" anisotropy have been discussed [4].

It was found that in $Nd_2Fe_{14}B$ single crystal by low-temperatures the coercivity of different domain walls essentially depends on their type and orientation. The role of the new domain wall types in the low-temperature magnetization reversal process in Fe-Nd-B permanent magnets is discussed.

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RARE EARTH 2:17 PERMANENT MAGNETS

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During the last four years we have undertaken a comprehensive and systematic study on precipitation hardened $Sm(Co,Fe,Cu, Zr)_z$ magnets and we are now in a position to completely understand the effects of composition and processing on their hard magnetic properties. Their high coercivity is due to a complex cellular/lamellar microstructure consisting of 2:17 R cells surrounded by 1:5 cell boundaries, superimposed on a thin lamella phase (Z phase). This microstructure causes domain wall pinning at the Cu substituted 1:5 cell boundaries because of a reduction in their domain wall energy, due to the Cu substitution. Higher ratio z leads to larger cells as expected due to the larger amount of the 2:17 phase. For a fixed Cu content, this translates to a larger amount of Cu in the1:5 cell boundaries, and therefore, to a higher coercivity. Magnets without Cu, but with Zr, have the cellular/lamellar microstructure. However, the coercivity of the magnets is almost zero due to the lack of a large gradient in domain wall energy across the 1:5 boundaries. Cu substitution leads to a slight decrease in cell size. Magnets with higher Cu have higher room temperature coercivity but poor temperature dependence of coercivity. Zr is critical in the formation of uniform cellular and lamellar microstructures. In Zr free samples, the lamellar microstructure is not formed, and a larger amount of Cu is needed to form the cellular microstructure. For higher Zr, a 2:7 phase is formed leading to a deterioration of magnetic properties. Increasing Fe content results in the formation of uniform cellular/lamellar microstructures with a larger cell size. This translates to a larger Cu content in the 1:5 cell boundaries and thus to a higher coercivity. For higher Fe, the coercivity sharply drops because of the deterioration of the cellular microstructure and magnetic properties of the 2:17 phase. In general, the homogenized magnets have a featureless microstructure with the hexagonal 2:17 phase. However, for the homogenized magnets with higher Cu and Zr content, a microstructure consisting of 1:5 precipitates embedded in the 2:17 matrix is observed. In the latter magnets, a shorter aging at 850°C followed by subsequent quenching is enough to develop a high coercivity of over 22 kOe. The results of all of these studies clearly show that Cu and Zr are important elements in developing and stabilizing a uniform cellular microstructure, and the Cu mainly controls both the coercivity and its temperature dependence.

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IT ALL STARTS WITH IRON.

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Edison attributed progress to 2 percent inspiration and 98 percent perspiration. In the electrical power industry under Edison the inspiration may have been as high as that, but for most of the last century it has been almost entirely perspiration that has led to advances in the use of soft magnetic metals for motors, generators and transformers.

In technology there is a chain linking theory, phenomenology, experiment and practice. In principle each of these feeds into its neighbor in the chain, but in electrical machinery based on soft magnetic metals, it seems that the experiments feed outwards in both directions without much feedback. There are many reasons for this. There are matters of the many disciplines involved, the complexity of the problems and the extremely wide range of length scales to be considered. The electrical power industry concerns range from atoms to real estate, from Dirac's equation to Federal Regulatory Commissions. economists. What ever happened to research in magnetism at (Over the past fifty years engineers and scientists have been replaced by lawyers and places like General Electric and Westinghouse)?

The thesis of this presentation is that there is a fundamental cause for all of the above. It is iron. Iron has the highest moment per unit volume or per unit mass and it is so readily available that it is almost free. So the history of soft magnetic metals for power applications, to be reviewed, is that of how to make iron better without making it a significant part of the cost of the motor, generator or transformer. The main path has been to purify it to get rid of the bad guys and to enlist the help of other cheap elements such as silicon to improve the metallurgical properties with a minimal reduction in magnetic moment and a substantial increase in electrical resistivity. More recently another cheap element, boron, has been used to change the crystal structure from body-centered-cubic (slightly tetragonal) to amorphous or nanocrystalline composites from the partial recrystallization of amorphous iron alloys.

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Nanocrystalline Soft Magnets

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Abstract

Nanocrystalline soft magnetic alloys will be presented and their application in power electronics will be discussed. These nanocrystalline (nc) alloys are prepared by proper heat treatment of an amorphous precursor containing both grain nucleating (Cu) and grain growth inhibiting (early transition metal, ETM : Zr, Nb, etc) elements. Two families of these nc alloys have been investigated so far; the Finemet type, ($Fe_{73.5}Si_{22.5-x}B_xNb_3Cu_1$, x=7 and 9) and Nanoperm type, ($Fe(Co)_{92-x-y-z}\ Zr_xNb_y\ B_zCu_1$, x=2,7, y=3.5, 4, z=2-8.5). (The version with Co replacement of Fe is called Hitperm)
These two-phase granular magnets composed of magnetic nanosized crystallites embedded in residual amorphous matrix shows interesting magnetic phase transitions evolving through strongly-coupled ferromagnetic, weakly-coupled "super"-ferromagnetic, superparamagnetic and paramagnetic states as a function of temperature. These transitions will be exemplified by the characteristic changes in the hysteresis loop characteristics (saturation magnetization, remanence ratio, coercive field, initial permeability) as a function of temperature. Special attention is paid to the explanation of the Hopkinson peak of the initial permeability, which limits the applicability of these soft magnetic materials well below the Curie temperature of the residual amorphous matrix. We report here a large (300-400 K) increase of the decoupling (T_c^{am}) temperature with increasing crystalline fraction in Nanoperm type alloys. This is in contrast to the Finemet type alloys where T_c^{am} varies several 10 K only around the original as cast amorphous T_c when the amorphous precursor is annealed around the first crystallization peak.
For electronic applications special tailoring of the hysteresis loop characteristics is necessary, which can be accomplished by transversal or longitudinal induced anisotropy's. For Finemet type alloys, the activation energy of field induced anisotropy is around 3 eV while that of the stress induced anisotropy is around 4 eV. By field annealing a relatively small amount of induced anisotropy, Ku~10-50 J/m^3, can be introduced only, useful in suppressing the dc bias sensitivity of transformer cores. By stress annealing however, a large induced anisotropy, up to K_u~ 4000 J/m^3, can be achieved, which beside excellent high frequency chracteristics, makes possible the application in power electronics as well like fly-back converters and smoothing chokes where storing of magnetic energy is necessary.
It is attempted that the cheap iron based nanocrystalline alloys should replace part of ferrites in the forthcoming years.

FROM NANOPARTICLES TO NANOCOMPOSITES

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Here we describe how the AC magnetic properties of nanoparticles are related to those of nanocomposites made by compaction. We start with an AC version of the Stoner-Wohlfarth model and show how the phase lag of the magnetization relative to the applied field leads to hysteresis or superparamagnetism, depending on the particle size, anisotropy, and temperature. These predictions are compared with experimental results for a 0.1% volume fraction sample of highly monodisperse 7 nm Fe nanoparticles at low temperature.

In contrast to this system with isolated, non-interacting grains, we also investigated a nanocomposite made by compaction of similar Fe nanoparticles. The frequency dependence of the coercivity, permeability, and power loss for a sample with an average grain size of 10 nm was measured between 77 and 473 K. Our AC magnetic model was modified to describe the nanocomposites as well, despite the presence of interactions among the grains. Here the volume was the exchange coupled volume rather than the particle volume, and the anisotropy was an effective value rather than the bulk magnetocrystalline anisotropy. The AC response of the nanocomposite is found to have two contributions, from magnetically isolated and magnetically coupled grains.

Related composites of $Fe_{10}Co_{90}$ nanoparticles were studied over a temperature range of 77 - 773 K. Here Lorentz microscopy of sectioned nanocomposites shows evidence of magnetically coupled regions. The temperature dependence of the effective anisotropy and the exchange length found the fits to the experimental data are presented, and discussed in terms of the random anisotropy model. We conclude with predictions of requirements for improved high temperature soft magnetic materials based on nanocomposites.

Soft Magnetic Materials for High Temperature Applications
Bulk Alloys, Nanocrystalline Alloys, and Fiber Reinforced Composites

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Abstract

Soft magnetic materials with superior high temperature magnetic and mechanical properties will play an important role in enabling a number of next generation aerospace technologies. Unfortunately, no known single phase material can simultaneously meet the anticipated requirements of a large saturation induction, large permeability, and low core loss in combination with high mechanical strength and creep resistance at temperatures as high as 600 °C. As a result, it now seems likely that in order to meet this goal a composite material will be needed in which the necessary magnetic and mechanical properties are associated with different constituents.

After reviewing the status of the best currently available commercial FeCo alloys, the preparation and properties of two different classes of composite materials will be described: nanocrystalline FeCo based Finemet-type materials and FeCo coated continuous W fibers. While each of these materials exhibit superior high temperature magnetic properties, it appears that the FeCo coated W fibers offers the most promising approach for also achieving high temperature mechanical strength and creep resistance.

Optimizing the energy product of nanocomposite magnets at finite temperature

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Abstract

We discuss the corecive behaviour of nanocomposite magnets. The focus will be on optimizing the energy product of these systems. We discuss results of finite temperture Monte Carlo simulation for the switching field of multilayers of hard and soft magnets. (J. Appl. Phys. August, 2000) These switching fields are usually larger than the depinning field of the domain walls in the same systems that we previously calculated (J. Phys. Conds. Matt. 11, 2719 (1999)) and have a different dependence on the soft layer thickness. In the former case, the switching field goes down as the soft layer thickness is increased. In the latter case the depinning field increases first and flattens off. Similar results also hold for three dimensional systems. In this case the depinning field exhibits a maximum as a function of the soft layer thickness. The implication of this on designing the maximum energy product will be discussed. The effect of finite temperature and the dipolar interaction will be included.

“GAS ATOMIZATION TECHNIQUES AND SINTERING”

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ABSTRACT unavailable at the time of printing.

Magnetic Annealing

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Magnetic annealing - the thermal treatment of a magnetic material at a temperature below Curie temperature - generally results in the induction of a macroscopic magnetic anisotropy with a predetermined easy axis direction. The interaction between magnetic moments and microstructural topology favors the formation of atomic pairs in a direction, which is related to the orientation of constituent magnetic moments.

The anisotropy induced by magnetic annealing is characterized by a preferred direction, which is parallel with the field direction during annealing. The magnitude of the induced anisotropy constant is a function of time and temperature of the treatment. Normally, this induced anisotropy is reversible and can be removed by other annealing applying the magnetic field in another directions. The origin of the field - induced anisotropy has been ascribed to the formation of atom pairs aligned along a preferred direction determined by the direction of the applied magnetic field during anneling.

The magnetic annealing can be applied by increasing the temperature of the sample, which is introduced in an oven and applying a magnetic field by means of one solenoid, coils or electromagnet. Another possibility is to heat the sample passing a current through it (Joule heating), used also for the production of a circumferential magnetic field or by applying from outside a supplimentary one.

New results on the magnetic annealing in amorphous and nanocrystalline materials in the shape of ribbons, wires, glass-covered amorphous wires are presented.

NANOSTRUCTURED MAGNETIC MATERIALS USING ELECTRODEPOSITION PROCESSES.

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The last ten years have clearly revealed the technological potentials of nanostructured materials. However, the developments in some technological fields are still in desperate need of synthesis processes that can generate large amount of fully dense nanostructured products. This is the case for instance for soft magnetic materials. It has been showed a number of years ago, that by decreasing the average crystal size of soft magnetic materials in the nanometer regime, it is possible to reduce drastically their magnetic losses. However, many studies done in recent years have demonstrated that large-scale soft magnets can not be obtained by the densification of nanostructured powders. On the other hand, a number of works have showed that by controlling the current profile during electrodeposition and through the addition of grain growth inhibitors, it is possible to control the nucleation and growth of the deposited materials. Dense samples, with a crystalline size as low as 5 to 7 nm, can thus be synthesized. Compared to other techniques, pulse-electrodeposition has received little attention as a synthesis method for producing large quantities of fully dense nanostructured materials. In this work we will discuss the synthesis of soft magnetic materials, in particular Fe and Fe-riched Fe-Ni alloys obtained by controlling different electrodeposition parameters. These examples will demonstrate that electrolytic processes can be the major synthesis technique for large-scale development of dense nanostructured materials.

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